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Effectiveness of Fuel Treatments for Mitigating Wildfire Severity: A Manager-Focused Review and Synthesis

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Abstract

The 2008 Request for Applications from the Joint Fire Science Program called for a synthesis of the extant literature that addresses the effectiveness of fuel treatments. We employed a four-pronged approach to address this task, including several scoping exercises with land managers, a literature review, a meta-analysis, and development of an online pictorial database.

Background and Purpose

Changes in land use and management over the last century or more have increased the vertical and horizontal continuity of wildland fuels in many areas of North America (Pyne 1982, but see Keeley and Fotheringham (2001) and Johnson and others (2001) for discussion of exceptions). This increase in fuel hazard is compounding with climate change (Brown and others 2004) and ex-urban development (Cova and others 2004) to place ever more values at risk to wildfire damages. Land managers have responded to political demands for an expansion of efforts to mitigate fuel hazards (USDA Forest Service 2000), piquing the interest for more research into the effects and effectiveness of these activities (Botti and others 1998). Consequently, the volume of fuel treatment studies has expanded greatly over the past decade (Figure 1). The 2008 Request for Applications from the Joint Fire Science Program called for a synthesis of the extant literature that addresses the effectiveness of fuel treatments. While a number of traditional literature reviews have been compiled on this topic (Keeley and others 2009; Agee and Skinner 2005; Peterson and others 2005; Graham and others 2004; Carey and Schumann 2003; Fernandez and Botelho 2003, Greenlee and Sapsis 1996), reviews such as these are inherently qualitative. They are also prone to bias in selection and interpretation of findings and tend to over-emphasize contradictory conclusions with inadequate attention to sources of variability (Cooper and others 2009). Since 1955 the medical sciences have relied instead on an alternative approach to research synthesis using the techniques of meta-analysis (Stroup and others 2000).

Meta-analysis is a systematic and quantitative approach to research synthesis that provides a method for the combination and comparison of results from independent trials to assess the direction, magnitude, and consistency of reported responses (Cooper and others 2009). It is now commonly applied to ecological questions (Gurevitch and others 2001) and has been recently applied to the wildland fuels treatment literature, as well (Martinson 1998, Wan and others 2001, Kopper 2002, Boerner and others 2009, Kallies and others 2010, Youngblood 2010). Kopper and others (2009) conducted a meta-analysis on the effects of prescribed fire on fuel reduction. The focus of this project was a meta-analysis of the literature documenting fuel treatment performance in mitigating subsequent fire intensity and severity to assess the quantitative support for the current fuel management paradigm. Meta-analysis allowed us to test the expectation that fuel treatment effectiveness will vary predictably in different types of vegetation and by the degree to which a less hazardous condition is created through reducing surface fuels, removing ladders, opening canopies, and selecting for fire resistance (Agee and Skinner 2005).

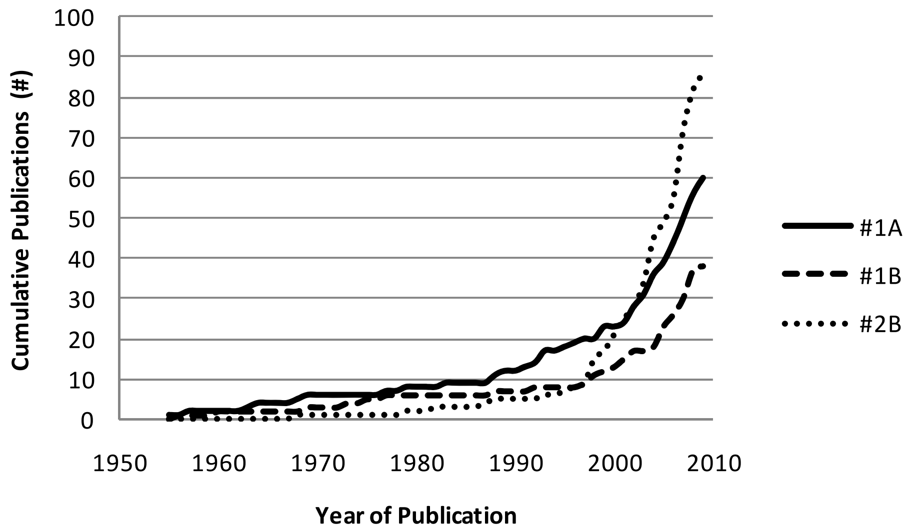

Figure 1. Cumulative number of fuel treatment effectiveness publications by year and type of study: 1A = observed wildfire response to actual fuel treatment, 1B = simulated wildfire response to actual fuel treatment, 2B = simulated wildfire response to hypothetical fuel treatment.

Study Description

Meta-analysis involves a comprehensive literature search for relevant studies, quantification of the magnitude of effects reported in the studies selected for inclusion, and an analysis of study heterogeneity to identify the strength and significance of any emergent trends. We reviewed over 1,200 publications in our search for studies relevant to our synthesis on fuel treatment effectiveness. We found 60 that documented the performance of actual fuel treatments exposed to actual fire. Nineteen (Appendix A) of these met our criteria for inclusion by providing evidence of control for variations in weather and topography and reporting results in comparable terms of crown volume scorch, scorch height, or flame length measurements. Studies based solely on interpretation from remotely sensed imagery were excluded as lacking a compatible level of control and the results of modeling exercises were excluded as we were primarily interested in assessing the empirical evidence of fuel treatment performance.

Central to any meta-analysis is the calculation of effect sizes: dimensionless measures of the magnitude of difference between treatment and control means. We employed the log response ratio (Hedges and others 1999) for this meta-analysis, calculated by dividing the response measurement from the treatment by the response measurement from the untreated comparison, with the ratio transformed by its natural log.

Many of the 19 studies selected for inclusion in the meta-analysis included information from more than one treatment type and these were considered independent observations such that a total of 62 were included and their distribution among vegetation, region, and treatment categories is displayed in Table 2. Our primary hypothesis was that there would be differences in effects reported from different types of ecosystems, as defined by broad categories of geographic location (Northwestern US, Southwestern US, Eastern US, non-US) and vegetation (i.e., long-needle conifer forests, mixed conifer forests, other woodlands, shrublands, grasslands). We also hypothesized that fuel treatment effects would vary among different types of fuel treatment. Treatments were categorized for comparisons into six broad types based on the expected change to canopy and surface fuels, then ordered by expected effectiveness (Table 2). Any remaining variability in effect sizes within the vegetation and treatment categories was explored for relationships to treatment age and treatment intensity as indicated by changes to measured fuel conditions (surface fuel load and depth, residual tree diameters, height to canopy, stand density, and canopy bulk density).

Table 2. Distribution of observations included in the meta-analysis among treatment type categories within vegetation and region groups.

	Treatment Type[1]						
	1	2	3	4	5	6	Total
Vegetation							
Long-needle pine	6	12	1	1	0	3	23
Mixed conifer	7	6	1	0	3	13	30
Other woodlands	0	2	0	2	0	1	5
Grasslands	0	2	0	2	0	0	4
Total	13	22	2	5	3	17	62
Region							
Northwest US	7	6	2	1	3	7	26
Southwest US	6	8	0	0	0	9	23
Eastern US	0	3	0	4	0	1	8
Non-US	0	5	0	0	0	0	5

[1] **Treatment descriptions in order of expected effectiveness:**

1. Canopy thinned with slash and surface fuels reduced by broadcast burning.
2. Canopy untreated, but surface fuels reduced by underburning or grazing/browsing by livestock or other biological vectors.
3. Canopy thinned with activity fuels removed by whole tree extraction, yarding, or piling and burning of slash.
4. Canopy untreated, but surface fuels rearranged by physical or chemical means (mastication, chipping, crushing, piling, herbicide application).
5. Canopy thinned with slash and surface fuels rearranged as above.
6. Canopy thinned with no treatment of the activity fuels added to the surface.

Our meta-analysis was useful for quantifying the size and significance of treatment effects published in the literature, as well as identifying the most influential variables. However, it was clear from several scoping exercises with land managers that meta-analytic output would be most meaningful if supported by photographic comparisons. As a complement to our meta-analysis we therefore also constructed a searchable database of photographs from plots sampled in support of two previous JFSP projects (Omi and Martinson 2002, Omi and others

2006). The database contains 124 photo pairs from adjacent treated and untreated stands that were affected by nine different wildfires. Photos may be selected by specifying search criteria for location, cover type, treatment type, treatment age, and/or wildfire weather conditions (percentile of the Burning Index on the day plots were burned relative to the local historic distribution). Search options for location include Northwest, Southwest, Rocky Mountains, and/or Southeast. Cover type options include mixed conifer forest, mixed pine forest, ponderosa pine forest, ponderosa pine woodland, and/or slash pine forest. Treatment types include canopy thinning followed by slash treatment, canopy thinning without slash treatment, and/or surface treatment only. Treatment ages span from 0 to 20 years and any narrower range may be specified. Wildfire weather conditions range from 65% to 100% of the historic distribution for the Burning Index and any narrower range for this variable may be specified, as well.

The database is housed online and the homepage displays a map of the wildfire locations with pop-up identifiers, the selection criteria options defaulted to return all 124 photo pairs, and a summary of each location matching the selected search criteria (Appendix B1). A detailed description of each plot may be requested that displays a new page with a set of four photographs showing treated and untreated post-fire conditions, a numeric comparison table of treated versus untreated stand measurements (tree density, mean DBH, canopy base height, and canopy bulk density), and a scalable location map with satellite imagery that may be zoomed to discern individual trees (Appendix B2). The interested viewer may also select to display a graphic that shows the relative effectiveness of the selected treatment in statistical terms that correspond to the effect sizes used in our meta-analysis.

Key Findings

Our meta-analysis demonstrates wide variability in fuel treatment effects that have been reported in the literature and quantifies the relative effectiveness of different types of fuel treatments in various ecosystems. The overall mean effect of fuel treatments on fire responses is large and significant, equating to a reduction in canopy volume scorch from 100% in an untreated stand to 40% in a treated stand, a reduction in scorch height from 30 m to 16 m, or an inferred reduction in flame length from 11 ft to 7 ft. However, the extreme case of treatment effectiveness reported a reduction in crown volume scorch from 85% in untreated areas to less than 1% in an adjacent treated stand (an effect size 7.5 times larger than the mean), while the extreme case of treatment ineffectiveness reported an increase in flame length from less than a foot in untreated fuels to 2.5 feet in treated fuels (an effect size 3.2 times greater than the mean and in the opposite direction). Eight of the 62 observations included in our meta-analysis demonstrated such counter-productive treatment effects, including 4 of the 17 studies in untreated slash, 1 of the 3 studies where slash was left in piles, 1 of 3 studies in masticated fuels, 1 of 3 studies of underburns more than 10 years old, and 1 of 17 studies of more recent underburns.

The most informative (Burnham and Anderson 2003) grouping of fuel treatment effectiveness studies distinguished three vegetation types (grasslands, conifer forests, and woodlands other than conifer forests), and three types of fuel treatment (recent surface fuels reduced by burning or grazing less than 10 years prior to wildfire, recent surface reduction preceded by heavy thinning, and other treatments that did not include recent surface fuel reduction including mechanical rearrangement and thinning with no or old slash treatments). The resultant meta-analytic model is highly significant (p<0.001) and explains 78% of the variability in reported observations of fuel treatment effectiveness (Figure 2).

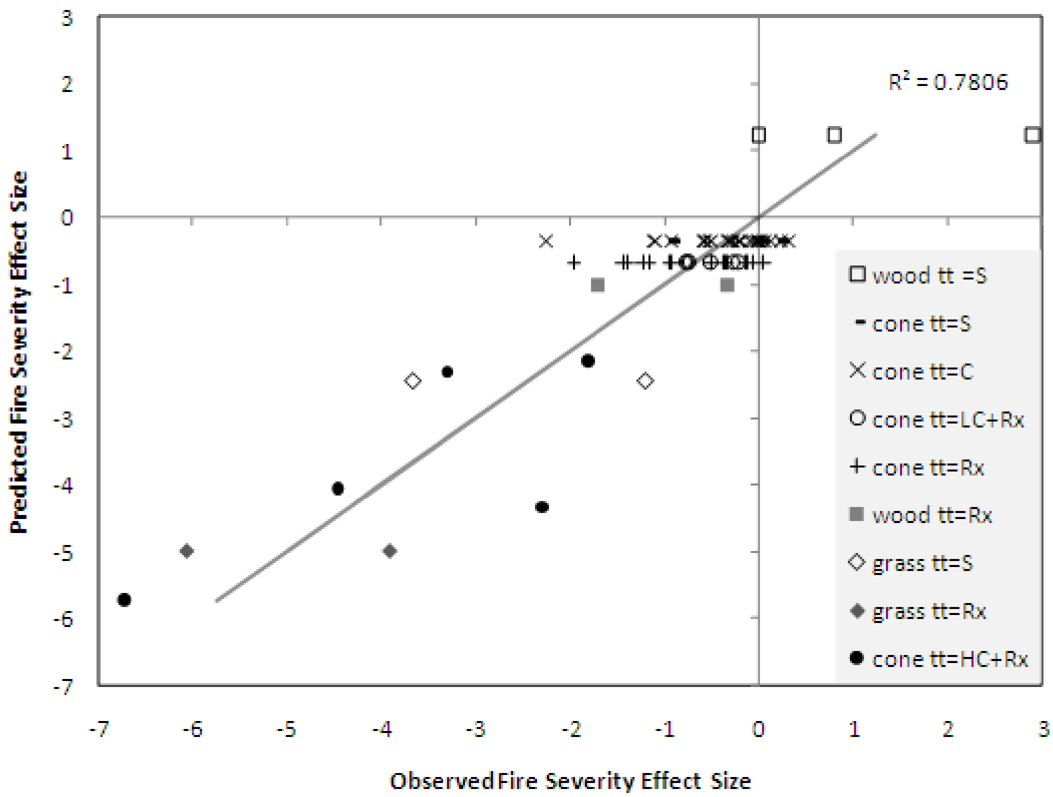

Figure 2. Predicted versus observed fuel treatment effect sizes on fire severity (negative values indicate lower severity in a treated area). Legend abbreviations are as follows: cone = conifer forest, wood = woodland other than conifer forest, grass = grassland, C = canopy thin, HC = heavy thin, LC = light thin, Rx = recent surface fuel reduction, S = surface fuel treatment other than recent reduction.

Treatments have proved most effective in grasslands and conifer forests that were heavily thinned and subsequently burned. The least effective treatments have been mechanical rearrangement in woodlands and forest thinning where slash was left untreated. However, the latter have not been as generally counter-productive as asserted in previous literature reviews, as over 70% of the observations from such treatments reported a moderated fire response.

A threshold was identified for effective canopy thinning when followed by broadcast burning of the surface fuels. These combination treatments that achieve a 100% change to a less hazardous stand condition increased in effectiveness as fuel hazard decreased (as measured by the average change to mean tree diameter, height to canopy, and canopy bulk density). Lighter thinning treatments that fail to effect a reduction in fuel hazard of at least 123% appear to perform no differently than surface reduction treatments that did not include any mechanical thinning (Figure 3). Based on the average stand conditions in untreated stands, the necessary thinning intensity to achieve any benefit beyond what would be produced by the surface treatment alone corresponds to an increase in mean tree diameter from 19 cm to 42 cm, an increase in height to canopy from 4 m to 9 m, and a decrease in canopy bulk density from 0.09 kg/m^3 to 0.04 kg/m^3. No relationship was found between thinning intensity and subsequent fire response among the thin-only treatments, suggesting that any benefit from the reduction in canopy fuels is offset by the increase in surface fuels.

Recent surface fuel reduction treatments were found to consistently moderate subsequent fire behavior in all the broad vegetation types included in our synthesis. The effectiveness of these treatments shows a weak relationship to changes in mean tree diameter (r^2 = 0.28), but is unrelated to canopy fuel conditions (Figure 3).

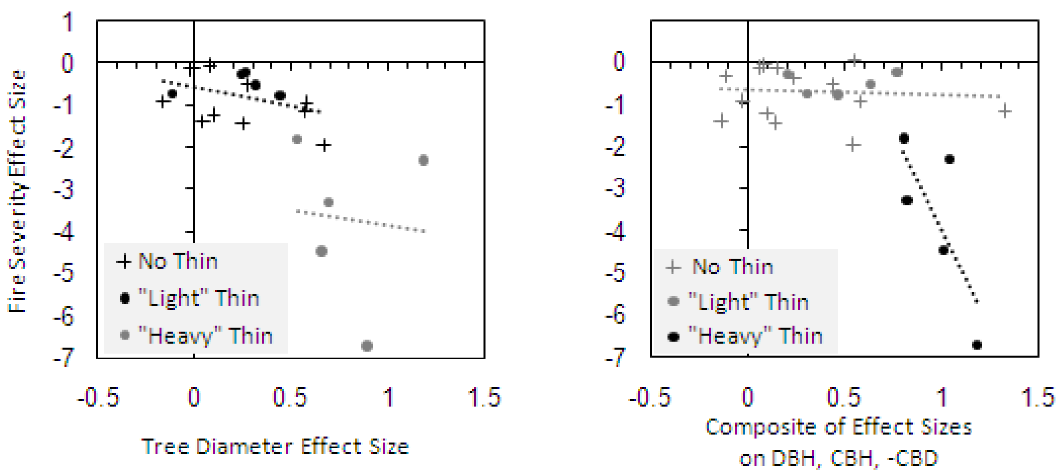

Figure 3. Scatter plots of fire severity effect sizes versus two measures of treatment intensity for treatments that included recent surface reduction in conifer forests, whether preceded by heavy thinning (composite of the effect sizes on residual tree diameter (DBH), height to canopy (CBH), and inverted canopy bulk density (-CBD) >=0.80), "light thinning" (composite intensity <0.8), or no thinning.

Surprisingly, no differences in treatment effectiveness were found between long-needle pine and mixed conifer forests or between the northwestern and southwestern regions when treatment type and age were considered.

Relationship of Findings to Current Paradigm

The fuels management paradigm that has emerged from previous literature reviews emphasizes the importance of first distinguishing ecosystems where fire is limited primarily by fuel quantity and was historically frequent and benign (e.g., dry conifer forests) from those where fire is limited more by climate and was historically infrequent and stand-replacing (e.g., sub-arctic and sub-alpine forests, California Chaparral). The paradigm suggests that fuels management may be inappropriate and counter-productive in the latter types of ecosystems (Keeley and Fotheringham (2001) and Johnson and others (2001)), but should be successful in the former to the degree that more resilient conditions result from reducing surface fuels, removing ladders, opening canopies, and selecting for fire resistance (e.g., leaving large trees), in that order (Agee and Skinner 2005). Keeley and others (2009) note that empirical studies in lower elevation western conifer forests consistently demonstrate reduced wildfire severity from combinations of thinning and burning, but caution that the slash produced by thinning will exacerbate fire hazard until it is also treated. Guidance has been less clear for ecosystems where the interactions among fire, weather, and fuels is more complex and the historic fire regime was a mixture of frequencies and severities (e.g., mesic mixed forests at middle elevations and latitudes), thus the recommendation for fuels management in these systems has been for limited and cautious application (Schoennagel and others 2004).

However, previous reviews of the literature on fuel treatment effectiveness have noted above all a paucity of empirical data and heavy reliance on anecdote, theory, and modeling (Carey and Schumann 2003, Martinson and Omi 2003, Graham and others 2004, Peterson and others 2005). Martinson and Omi (2003) abandoned an initial attempt to conduct a meta-analysis on this topic due to the lack of comparable quantitative information. But the literature on fuel treatment effectiveness has expanded considerably in the last few years and the number of studies (19) we were able to include in this meta-analysis is comparable to others that have recently been conducted on fuel treatment topics (22 in Kalies and others' (2009) meta-analysis of wildlife responses, 12 in Boerner and others' (2009) meta-analysis of effects on soil properties, 8 in Kopper and others' (2009) meta-analysis of effects on fuel loads, and 7 in Youngblood's (2009) meta-analysis of effects on diameter distributions). Our synthesis of fuel treatment effectiveness studies highlights several considerations that both support and inform the current fuels management paradigm.

Our synthesis demonstrates that fuel treatments vary widely in effectiveness and the variability is best explained by vegetation type. The relative effectiveness of treatments in grasslands, conifer forests, and woodlands is as would be expected from the hypothesis that treatments will be most effective where available fuel accumulates most rapidly and fire was historically most frequent, based on coarse fire regime constructs (e.g., Schmidt and others 2002). However, we were surprised to find no differences in fuel treatment effectiveness between long-needle pine and mixed conifer forests or between the northern and southern latitudes of the western US. This suggests that fuel treatment effectiveness may be less sensitive to climatic gradients in western forests than has been suggested in previous reviews (Schoennagel and others 2004). However, none of the studies included in our synthesis extended into the upper elevations or latitudes dominated by short-needle conifers where fire frequency was historically least frequent. One anecdote from such systems suggests that thinning may exacerbate fire behavior (Alexander and Lanoville 2004), but data have not been presented that could be included in our synthesis.

That no relationship (r^2<0.06) was found between canopy fuel variables and the effectiveness of either surface reduction treatments without thinning or thinning treatments without subsequent slash treatment supports the assertion that surface fuel reduction is of primary importance in influencing treatment effectiveness. Much of the variability within these treatment types would likely be explained by the amount of change in surface fuels that was actually produced, but surface fuels information was not reported with enough consistency to include in our synthesis as they generally cannot be reconstructed in retrospective studies (Martinson and Omi 2008).

However, it is notable that more often than not, thin-only treatments have been found to moderate fire responses in spite of the addition of slash fuels to the surface, though to a lesser degree than surface reduction treatments with or without prior thinning. The effectiveness of thin-only treatments likely depends on whether fire enters the treated stand as an active crown fire or as a surface fire, as the additional surface fuels increase the likelihood of torching, but the more open canopy reduces the likelihood of sustained crown fire (Scott and Reinhardt 2001).

The best available predictor of the effectiveness of surface reduction treatments was residual tree diameter. This variable was also included along with canopy variables as a predictor of the effectiveness of treatments that combined thinning and burning. Thus, the recommendation to favor retaining large trees over small ones in order to improve the fire resistance of treated stands is supported. Thinning followed by burning was found to be the most effective type of treatment, as expected, but the added benefit of thinning does appear to depend upon achieving a substantial change to canopy fuel conditions.

Management Implications

The results of this synthesis add empirical support for the basic principles of fuels management proposed by Agee and Skinner (2005) that emphasize the reduction of surface fuels and the preservation of the largest trees in a stand, but also recognize the importance of opening the canopy in order to achieve the maximum benefits of hazard reduction. It also confirms that all treatments may not be beneficial in all locations and provides a quantifiable estimate of the expected relative effectiveness of different types of treatment in broad vegetation categories. Caution is warranted in ecosystems other than long-needle pine and mixed conifer forests due to the lack of empirical information on treatment effectiveness and the potential for negative ecological consequences, such as invasion by more flammable non-native species (Martinson and others 2008).

But treatments that include surface fuel reduction, particularly by prescribed burning, are well supported for moderating potential wildfire behavior in both long-needle pine and mixed conifer forests. These treatments appear to remain effective for up to ten years, but longevity should be expected to vary by ecosystem productivity. Where crown fire hazard has become so high as to preclude initial entry with prescribed fire, mechanical thinning may be a necessary precursor. Thinning treatments have demonstrated the most substantial reductions in wildfire severity, but only by those that produce substantial changes to canopy fuels, shift the diameter distribution towards larger trees, and are followed by broadcast burning. Until the residual activity fuels are disposed they will largely offset much of the hazard reduction benefit achieved from opening the canopy. While follow-up slash treatment may be generally intended, untreated slash seems to be encountered by large wildfires with surprising frequency (Table 1).

Modifications in fire behavior achieved within a single treated stand, however significant, are unlikely to change the area ultimately burned by a large wildfire, aid fire control efforts, or impact the distribution of severities across a landscape (Finney and others 2003). Fuel treatment effectiveness ultimately depends on the cumulative impact of a treatment regime applied across landscapes and maintained through time. Optimization and assessment of treatment regimes rely on models that presume treatments will perform as expected (Finney and others 2007). Empirical fuel treatment performance studies, such as those included in this meta-analysis, help define the conditions under which theoretical expectations are met. Records of treatment boundaries, prescriptions, and fuel conditions are therefore critical components of fuel treatment implementation to enable effective adaptive management.

Additional Research Needs

Wildfires provide the best test of treatment performance under extreme conditions, but information from retrospective studies is limited to that provided by chance encounters. Such encounters are most likely where treatments and wildfires are most common, thus information is unevenly distributed among ecosystems, geographic locations, treatment types and treatment ages (Table 1). Our search for studies to include in this synthesis highlights the need for greater attention to identifying treatments encountered by wildfires in all areas other than long-needle pine and mixed conifer forests west of the Rocky Mountains. Also, alternatives to prescribed fire for treating surface fuels have so far received little evaluation in any ecosystem from a fuel hazard perspective. Few of the studies included in our synthesis documented more than a single treatment entry other than follow-up slash treatments and the relative effectiveness of initial entry treatments versus treatments that have been maintained at varying frequencies is in need of investigation as opportunities arise. The influence of treatment scale on modifying fire behavior both within treatments and beyond them is another consideration that has received little empirical evaluation.

Retrospective wildfire investigations are also limited by their maximum detectable response, which decreases with the height of the dominant vegetation, as well as their capacity to connect treatment effectiveness to the altered condition of any fuels the wildfire consumes. An ideal evaluation of fuel treatment effectiveness would include measurement of all fuelbed components that contribute to flammability, compare potential fire behavior in treated and untreated fuelbeds with predictive models, and compare model predictions to observations from experimental fires or serendipitous wildfire events. Direct measurement of fire behavior is the only comparable means to evaluate fuel treatment performance in non-forest ecosystems and is a worthy research endeavor in all, despite a high potential for failure to fully meet experimental objectives (Fites and Henson 2004).

Deliverables

Table 2. Deliverables crosswalk.

Proposed	Status
1 Website with photographic database	Available online at http://omiassociates.net/fueltreatment/
1 Multimedia DVD containing synthesis document and photographic database	Will be delivered to JFSP upon submission of meta-analysis manuscript
2 Presentations to land managers	1 Oral presentation and 1 Poster presentation delivered at 4th Fire Congress in Savannah, GA November 30-December 4, 2009
1 Final report to JFSP	This document
2 Publishable manuscripts	Omi PN, Miller M, Martinson EJ, and Kaufmann MR. In prep. The science of fuel treatments: a retrospective and look ahead. International Journal of Wildland Fire. Martinson, EJ and PN Omi. In prep. Meta-analysis of fuel treatment effectiveness for mitigating wildfire severity.

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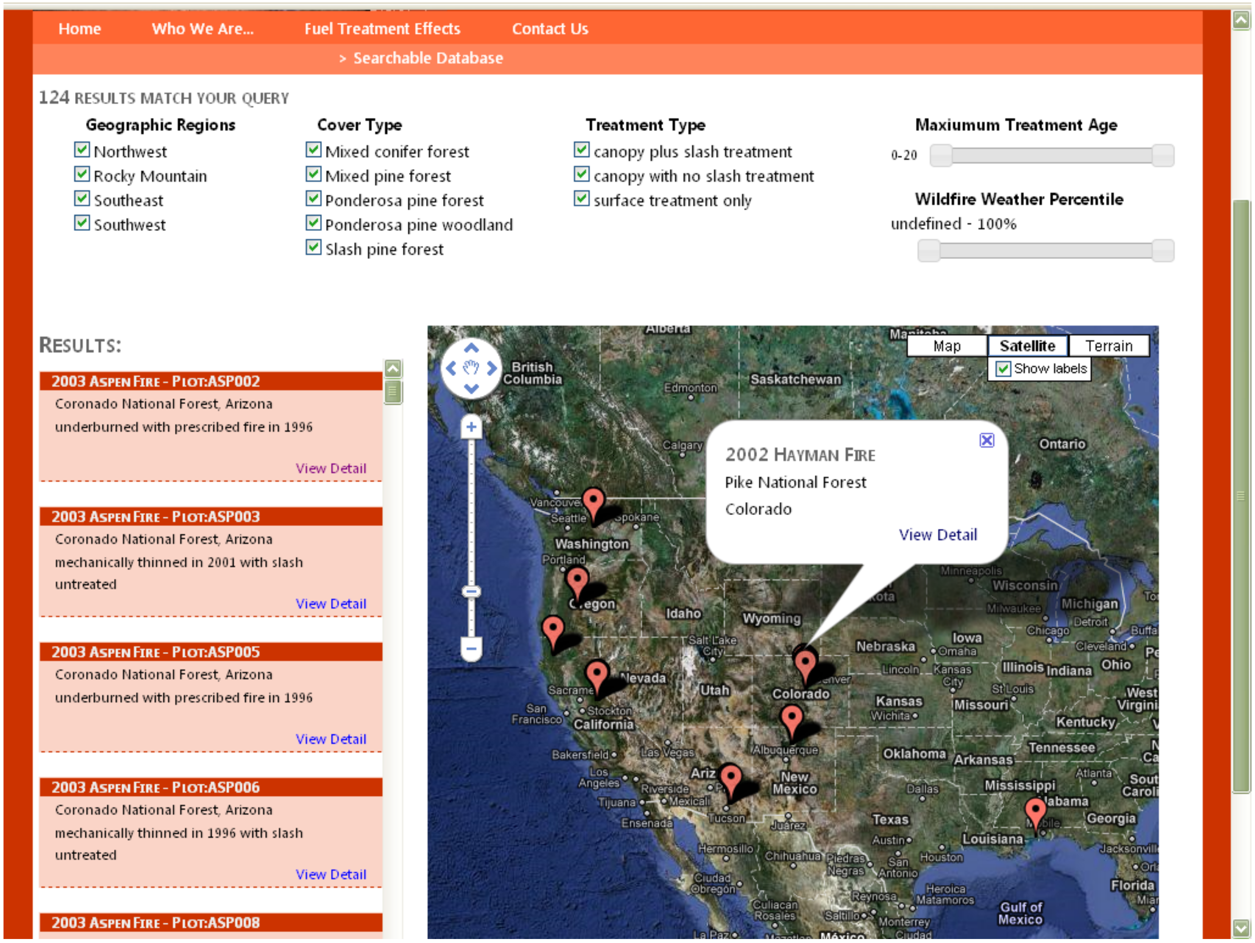
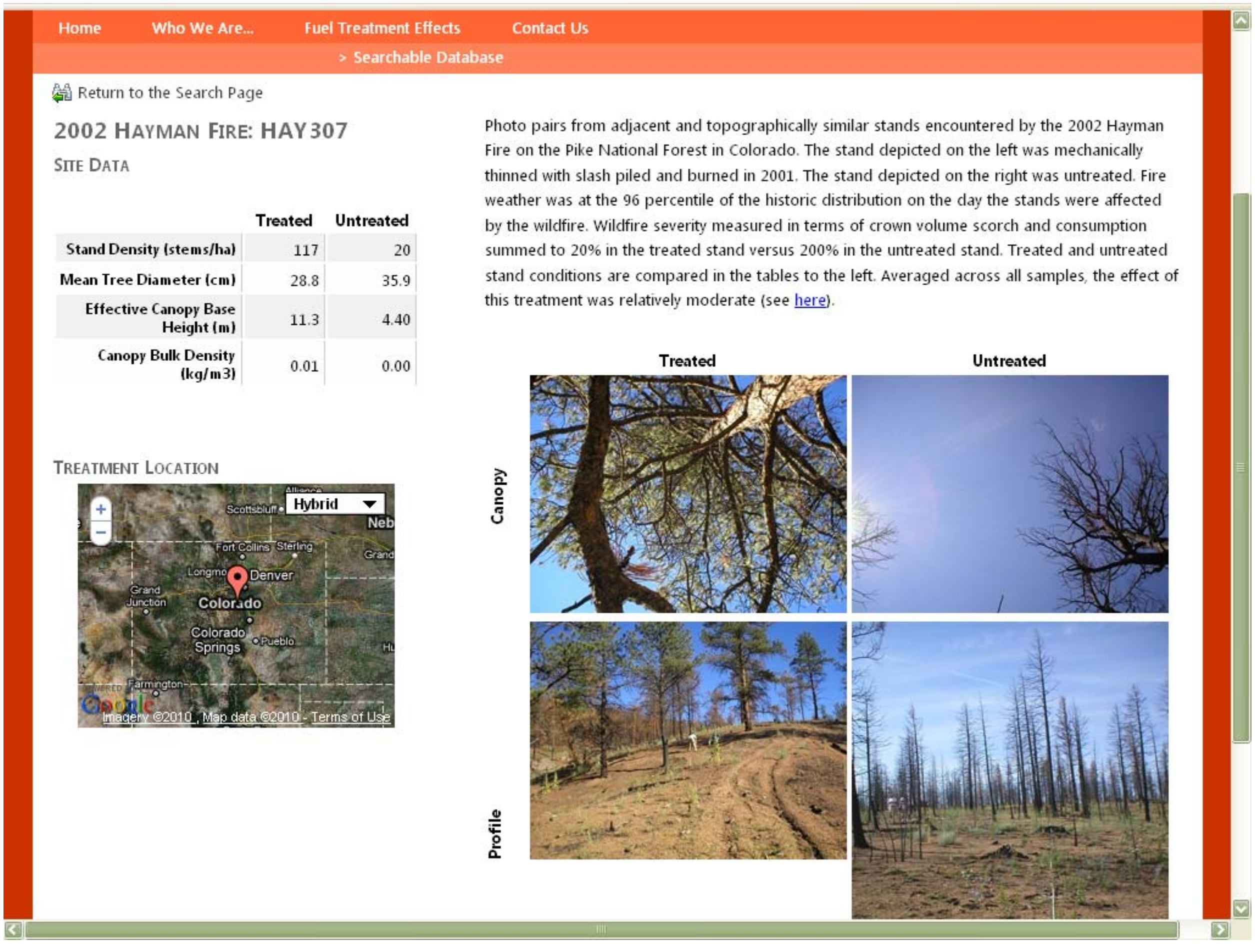
Appendix B1. Homepage for online searchable database of photographs documenting fuel treatment performance in wildfires.



Appendix B2. Detailed description and photographs from a selected treatment.



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> Searchable Database

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2002 Hayman Fire: HAY307

Site Data

	Treated	Untreated
Stand Density (stems/ha)	117	20
Mean Tree Diameter (cm)	28.8	35.9
Effective Canopy Base Height (m)	11.3	4.40
Canopy Bulk Density (kg/m3)	0.01	0.00

Treatment Location

Photo pairs from adjacent and topographically similar stands encountered by the 2002 Hayman Fire on the Pike National Forest in Colorado. The stand depicted on the left was mechanically thinned with slash piled and burned in 2001. The stand depicted on the right was untreated. Fire weather was at the 96 percentile of the historic distribution on the day the stands were affected by the wildfire. Wildfire severity measured in terms of crown volume scorch and consumption summed to 20% in the treated stand versus 200% in the untreated stand. Treated and untreated stand conditions are compared in the tables to the left. Averaged across all samples, the effect of this treatment was relatively moderate (see here).